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REPORT 1362

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By LEONARD K. TOWER, ROLAND BREITWIESER,
and BENSON E. GAMMON

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Lewis Flight Propulsion Laboratory
Cleveland, Ohio

National Advisory Committee for Aeronautics

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REPORT 1362

THEORETICAL COMBUSTION PERFORMANCE OF SEVERAL HIGH-ENERGY FUELS FOR RAMJET ENGINES [1]

By Leonard K. Tower, Roland Breitwieser, and Benson E. Gammon

SUMMARY

An analytical evaluation of the theoretical ramjet performance of magnesium, magnesium—octene-1 slurries, aluminum, aluminum—octene-1 slurries, boron, boron—octene-1 slurries, carbon, hydrogen, α-methylnaphthalene, diborane, pentaborane, and octene-1 is presented herein. Combustion temperature, air specific-impulse, and fuel specific-impulse data are presented for each fuel over a range of equivalence ratios at an inlet air temperature of 560° R and a combustion pressure of 2 atmospheres.

It was assumed that chemical equilibrium was attained during the combustion but that the expansion in the exhaust nozzle occurred with composition fixed. Thermal and velocity equilibrium was assumed between gases and condensed phases at all times.

Magnesium, magnesium—octene-1 slurries, aluminum, aluminum—octene-1 slurries, boron, boron—octene-1 slurries, pentaborane, diborane, and hydrogen provide air specific impulses exceeding those of octene-1. At any fixed air specific impulse below 152 seconds, the fuel weight specific impulses of hydrogen, diborane, pentaborane, boron, and boron—octene-1 slurries are superior to octene-1. The fuel volume specific impulses of boron, aluminum, carbon, boron—octene-1 slurries, magnesium, pentaborane, α-methylnaphthalene, and magnesium—octene-1 slurries are superior to octene-1.

The effects of inlet air temperature and combustion pressure are investigated for some of the fuels. Because of the limited range of inlet conditions considered, means of extending these data to other inlet conditions are presented.

Determination of air specific-impulse efficiency and combustion efficiency for experimental combustion by means of the theoretical data herein is discussed. The use of the theoretical performance data in determining the relative flows of the various fuels to an engine operating at a fixed thrust level is described.

INTRODUCTION

The ever increasing performance required of high-speed aircraft places new demands upon the propulsion system. Improved range, thrust, combustion efficiency, and combustion stability characteristics may possibly be obtained by the use of the special jet-engine fuels. These materials promise advantages over conventional hydrocarbon fuels because of their higher heating values and because of the ease and stability of their combustion.

The use of special fuels is warranted for high-speed flight because the cost of the fuel is often only a small part of the total cost of aircraft operation. This is particularly true in the case of nonreturn guided missiles.

Various fuels of interest for air-breathing engines are certain light elements such as boron and aluminum, alloys and hydrides of these elements, and slurries or paintlike suspensions of the solid materials in a liquid hydrocarbon. The heating values of these substances are higher than those of the ordinary jet fuels on either a gravimetric or a volumetric basis. Hydrocarbons having a high volumetric heating value have also been of interest. Table I presents the heating values and certain physical properties for some of the fuels.

Considerable experimental work, summarized in reference 1, has been conducted with certain high-energy fuels to determine their suitability for selected applications in aircraft. The NACA Lewis laboratory has determined some of the physical properties and combustion properties of diborane, boron, magnesium, and aluminum (refs. 1 to 7). The metals were burned in the form of powder, wire, and slurries.

The theoretical performance of high-energy ramjet fuels is of interest both in evaluating experimental results and in judging the potentialities of proposed but untested materials. Theoretical comparisons of fuels burned in a great excess of cool air may be based upon conventional heating values of the fuel. However, when the temperatures obtained in the combustion process exceed about 3500° R, the mean molecular weight of gaseous products changes, and considerable energy is absorbed by dissociation, vaporization, and fusion. Thus, the theoretical performance of a fuel must be determined by an analytical method which can account for as many thermal effects as possible.

This report contains the theoretical performance for several potential ramjet fuels determined by such an analytical method. The combustion process was assumed to result in chemical equilibrium at the combustor outlet or exhaust-nozzle inlet. However, the composition throughout the expansion process was assumed to be fixed. It is customary in computing the theoretical thrust produced by a jet to assume either that equilibrium composition exists throughout the exhaust nozzle or that the composition is fixed. In real expansions, partial recombination of dissociated materials is obtained, but the reaction rates are insufficiently known for inclusion of this effect in theoretical calculations. In this

[1] Supersedes NACA Research Memorandums E51C12 by Benson E. Gammon, 1951; E51C23 by Benson E. Gammon, 1951; E51D25 by Benson E. Gammon, 1951; E51F05 by Benson E. Gammon, 1951; E52L08 by Roland Breitwieser, Sanford Gordon, and Benson E. Gammon, 1953; and E53G14 by Leonard K. Tower and Benson E. Gammon, 1953.

TABLE I.—HEATING VALUES AND PHYSICAL PROPERTIES OF SOME HIGH-ENERGY FUELS

[Except as noted, heats of combustion calculated from heats of formation at 25° C from ref. 15; melting and boiling points obtained from ref. 16.]

Fuel	Melting point, ° F	Boiling point, ° F	Specific gravity	Stoichiometric fuel-air ratio	Oxides (a)	Heat of combustion		
						Btu/lb	Btu/cu ft	Btu/lb air
Acetylene	−115.2	−118.5 (sublimes)	0.6208 (−119° F)	0.0755	CO_2, H_2O	20,734	803,556	1565
Aluminum	1219.5	4442	2.702	0.2608	Al_2O_3	13,309	2,244,979	3471
Beryllium	2332.4	5378	1.85	0.1307	BeO	29,140	3,365,447	3809
Boron	4172	4622	2.34	0.1046	B_2O_3	[b] 25,381	3,707,695	2655
Carbon (graphite)	6606–87 (sublimes)	7592	2.25	0.0871	CO_2	14,087	1,978,712	1227
Diborane	−265.9	−134.5	[c] 0.4315 (−134.3° F)	0.0669	B_2O_3, H_2O	[b] 31,591	850,988	2113
Hydrogen	−434.5	−423.0	0.070 (liquid)	0.0292	H_2O	51,571	225,364	1506
Lithium	367	2437±9	0.534	0.2013	Li_2O	18,460	615,396	3716
Lithium hydride	1256	----------	0.82	0.1152	Li_2O, H_2O	17,760	909,156	2046
Magnesium	1204	2025	1.74 (41° F)	0.3527	MgO	10,639	1,155,664	3752
Octene-1	−152.3	250.3	0.716 (68° F)	0.0678	CO_2, H_2O	[d] 18,999	818,606	1288
Pentaborane	−51.9	32 (66 mm Hg)	[c] 0.6233 (77° F)	0.0763	B_2O_3, H_2O	[d] 29,362	1,142,516	2240
Silicon	2588	4271	2.4	0.2035	SiO_2	13,170	1,973,234	2680
Silane	−301	−169.2	0.68 (−301° F)	0.1164	SiO_2, H_2O	17,160	728,463	1997
Titanium	3272	5432	4.5 (68° F)	0.3473	TiO_2	8,187	2,299,952	2843
α-Methylnaphthalene	−22.90	471.96	1.020	0.0764	CO_2, H_2O	17,015	1,083,462	1300

[a] CO_2 and H_2O gaseous at 77° F; other products condensed at 77° F.
[b] Computed from data in ref. 17.
[c] Data from ref. 18.
[d] Data from refs. 19 and 20.

report, the assumption of expansion with fixed composition results in conservatively low air specific impulse.

The theoretical performance for the following potential ramjet engine fuels is reported herein: octene-1, magnesium, magnesium—octene-1 slurries, aluminum, aluminum—octene-1 slurries, diborane, pentaborane, boron, boron—octene-1 slurries, hydrogen, α-methylnaphthalene, and carbon. A combustor-inlet air temperature of 560° R and a pressure of 2 atmospheres were chosen.

An extended range of combustor-inlet conditions was chosen for the performance calculations of some of the fuels to facilitate the evaluation of experimental data. Some examples are given of the manner in which this theoretical information can be used in the operation of engines and in the evaluation of experimental data.

SYMBOLS

A area, sq ft
C constant used in computing the stoichiometric fuel-air ratio of a slurry
F stream thrust, lb
g acceleration due to gravity, 32.17 ft/sec^2
H_i^o sum of sensible enthalpy and chemical energy at temperature t and at standard conditions, kcal/mole
M Mach number
m molecular weight of a constituent
$\overline{m}$ mean molecular weight
n number of moles of a constituent
p static pressure, lb/sq ft
R universal gas constant, 1545.33 ft-lb/(mole) (°R)
r weight fraction of solid fuel in slurry
S_a air specific impulse, lb-sec/lb air
$S_{f,v}$ fuel-volume specific impulse, lb-sec/cu ft fuel
$S_{f,w}$ fuel-weight specific impulse, lb-sec/lb fuel
T total temperature, °R
t static temperature, °R
V velocity, ft/sec
w weight flow, lb/sec
γ ratio of specific heats
η efficiency
η_{S_a} air-specific-impulse efficiency
ρ density, lb/cu ft
$\Phi(M)$ stream thrust correction factor to $M=1$
φ equivalence ratio, ratio of actual to stoichiometric fuel-air ratio

Subscripts:
a air
c combustion, combustor outlet
e exhaust-nozzle outlet
exp experimental
f fuel
g gas
i denotes ith constituent of combustion products
in engine inlet
l liquid
n net
s solid
st stoichiometric
t theoretical
v volume
w weight

Superscript:
$*$ denotes a station having a Mach number of unity

ANALYTICAL METHOD

Suitable thrust parameters for both theoretical and actual jet-engine fuel performance have been found to be air specific impulse and fuel specific impulse or total stream momentum per pound of air and per pound of fuel, respectively. Air specific impulse, defined for choked flow, is

$$S_a=\frac{1}{w_a}\left(pA+\frac{wV}{g}\right)^* \tag{1}$$

where

$$w=w_a+w_f$$

Fuel-weight specific impulse is defined as

$$S_{f,w}=\frac{1}{w_f}\left(pA+\frac{wV}{g}\right)^*=\frac{S_a}{\frac{w_f}{w_a}} \tag{2}$$

and fuel-volume specific impulse is defined as

$$S_{f,v}=\rho S_{f,w} \tag{3}$$

The density of slurries for use in equation (3), relating fuel-weight and fuel-volume specific impulse, was calculated thus:

$$\frac{1}{\rho_{\text{slurry}}}=\frac{\text{Fraction metal}}{\rho_{\text{metal}}}+\frac{\text{Fraction octene-1}}{\rho_{\text{octene-1}}} \tag{4}$$

Magnesium and aluminum slurries follow this relation up to about 80 percent metal by weight, and boron follows up to 60 percent metal by weight for metal powders now available.

Air specific impulse can also be expressed as

$$S_a=\left(1+\frac{w_f}{w_a}\right)\sqrt{\frac{2(\overline{\gamma}+1)RT_c}{\overline{\gamma}g\overline{m}}} \tag{5}$$

where $\overline{\gamma}$ is an effective ratio of specific heats. The net internal thrust of an engine can be determined from the relation

$$F_n=\Phi(M_e)w_aS_a-\left(pA+\frac{wV}{g}\right)_{in} \tag{6}$$

where $\Phi(M)$ is a function relating stream thrust at any station to stream thrust at a station having a Mach number of unity (see eqs. (A2) and (A3)). The significance and the utility of these concepts are discussed in more detail in reference 8.

The theoretical determination of air specific impulse and fuel specific impulse for the fuels considered herein involved two principal steps: (1) the combustion temperature and burned-product composition were determined at the assigned combustion pressure, and (2) an isentropic expansion in the exhaust nozzle to a throat Mach number of unity determined the exhaust-nozzle-outlet static temperature and velocity. The results of step (2) were used to compute air and fuel specific impulses.

The method of computing combustion temperature and composition was that of reference 9. A set of simultaneous equations was solved which involved mass balance, heat balance, pressure, phase changes, and dissociation of solid, liquid, and gaseous molecules. The necessary thermodynamic properties of almost all the dissociated and undissociated combustion products were taken from tables included in reference 9. An empirical equation given in reference 10 for the specific heat of magnesium oxide was used to obtain values of specific heat, enthalpy, and entropy for magnesium oxide; the standard-state entropy of magnesium oxide was taken from reference 11. The thermal properties for boric oxide (B_2O_3) were obtained from reference 12.

The following assumptions were made concerning the combustion process in order to simplify the analysis: (1) all fuels were pure; (2) the air was composed of 3.78 moles of nitrogen to every mole of oxygen; (3) combustor-inlet air velocity was negligible so that the combustion static and total temperatures were equal; (4) all gases were ideal; (5) combustion was adiabatic and complete, that is, chemical equilibrium was assumed; (6) when solids or liquids were present in the combustion products, the volume occupied by the condensed material was negligible; and (7) thermal and velocity equilibrium existed between the different phases.

The products of adiabatic combustion of each fuel which were considered possible in the computations of composition are listed in table II. They were gaseous except as noted. The nitrides of boron, magnesium, and aluminum were neglected because of inadequate thermodynamic data. For the same reason, dissociation, fusion, and vaporization of magnesium oxide were neglected.

The exhaust-nozzle-outlet temperature was determined by computing an isentropic expansion from the combustion temperature and pressure to a pressure giving a Mach number of unity. It was assumed that in the nozzle (1) composition was fixed during the expansion process, (2) the volume occupied by condensed materials was negligible, and (3) condensed materials were in thermal and velocity equilibrium with the gas phase. The jet velocity was then calculated by using the following equation (ref. 13):

$$\frac{V_e^*}{g}=294.98\sqrt{\left[\frac{\Sigma n_i(H_t^o)_i}{\Sigma n_i m_i}\right]_c-\left[\frac{\Sigma n_i(H_t^o)_i}{\Sigma n_i m_i}\right]_e} \tag{7}$$

The air specific impulse was then

$$S_a=\left(1+\frac{w_f}{w_a}\right)\left(\frac{V_e}{g}+\frac{Rt_e}{\overline{m}V_e}\right)^* \tag{8}$$

RESULTS AND DISCUSSION

The combustion performance of several high-energy fuels is presented in figures 1 to 6 for a combustor-inlet air temperature of 560° R and a pressure of 2 atmospheres.

MAGNESIUM, MAGNESIUM—OCTENE-1 SLURRIES, AND OCTENE-1

The combustion temperatures for magnesium, magnesium—octene-1 slurries, and octene-1 are shown in figure 1(a). The data are limited to a maximum combustion temperature of about 5500° R because of the lack of thermodynamic data as previously discussed.

Increasing the magnesium concentration in a magnesium—octene-1 slurry increased the combustion temperature at all equivalence ratios investigated. It is significant that the maximum combustion temperature for the magnesium slurries occurs at progressively higher equivalence ratios as the magnesium concentration is increased. In order to show this effect, the data were calculated at equivalence ratios exceeding 1.0. This effect is a result of the high heating

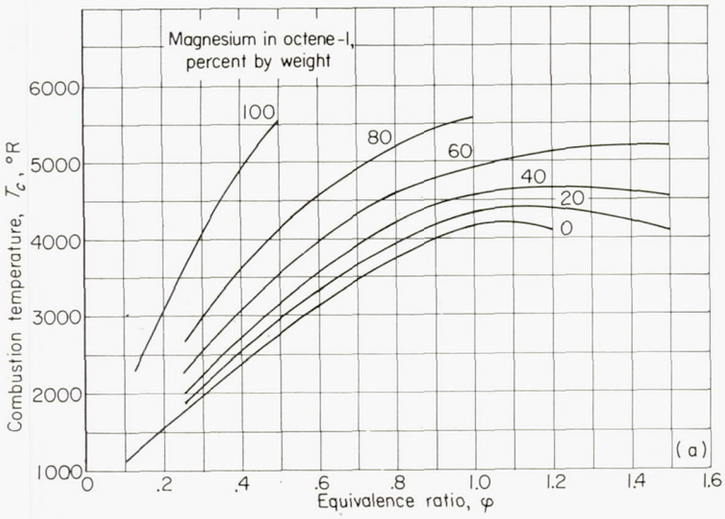
TABLE II.—PRODUCTS CONSIDERED POSSIBLE AS A RESULT OF ADIABATIC COMBUSTION

Product	Fuel										
(a)	Octene-1—α-methylnaphthalene	Boron	Pentaborane	Diborane	Hydrogen	Carbon	Magnesium slurry	Aluminum	Boron—octene-1 slurries	Aluminum—octene-1 slurries	Magnesium
O_2	x	x	x	x	x	x	x	x	x	x	x
N_2	x	x	x	x	x	x	x	x	x	x	x
CO_2	x	-----	-----	-----	-----	x	x	-----	x	x	-----
H_2O	x	-----	x	x	x	-----	x	-----	x	x	x
H_2	x	-----	x	x	x	-----	x	-----	x	x	-----
CO	x	-----	-----	-----	-----	x	x	-----	x	x	-----
C	x	-----	-----	-----	-----	x	x	-----	x	x	-----
H	x	-----	x	x	x	-----	x	-----	x	x	-----
O	x	x	x	x	x	x	x	x	x	x	x
N	x	x	x	x	x	x	x	x	x	x	x
OH	x	-----	x	x	x	-----	x	-----	x	x	-----
NO	x	x	x	x	x	x	x	x	x	x	x
$(MgO)_s$	-----	-----	-----	-----	-----	-----	x	-----	-----	-----	x
$(Al_2O_3)_{s,\,l,\,g}$	-----	-----	-----	-----	-----	-----	-----	x	-----	x	-----
Al	-----	-----	-----	-----	-----	-----	-----	x	-----	x	-----
AlO	-----	-----	-----	-----	-----	-----	-----	x	-----	x	-----
$(B_2O_3)_{s,\,l,\,g}$	-----	x	x	x	-----	-----	-----	-----	x	-----	-----
B	-----	x	x	x	-----	-----	-----	-----	x	-----	-----
BO	-----	x	x	x	-----	-----	-----	-----	x	-----	-----
BH	-----	-----	x	x	-----	-----	-----	-----	x	-----	-----

[a] Gaseous except as noted.

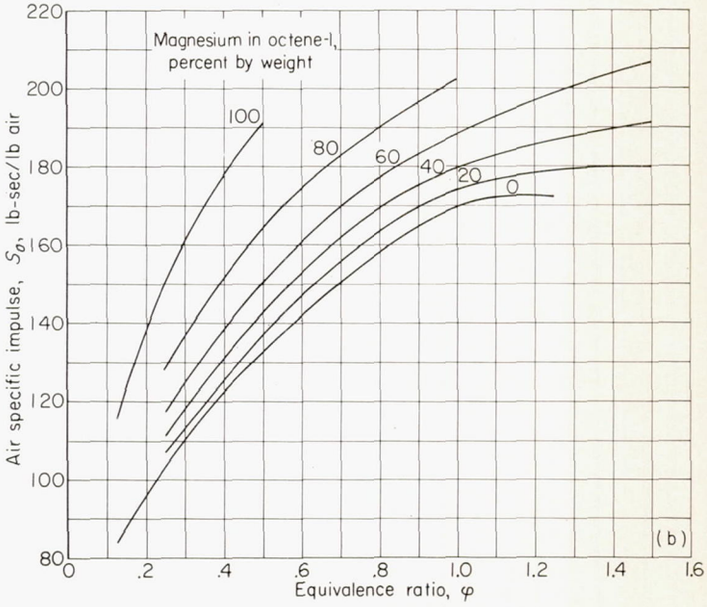
value of magnesium per pound of air since it was assumed that all magnesium combined with the oxygen present to form magnesium oxide. The tendency of high-concentration magnesium slurries to burn at equivalence ratios greater than 1.0 and to exhibit a higher heat release per pound of reactants than at an equivalence ratio of 1.0 has been experimentally established in reference 2. Reference 2 indicates that, for a slurry consisting of finely powdered magnesium suspended in a hydrocarbon fuel, magnesium burned preferentially with the oxygen present and hence permitted the high heat release.

Air specific-impulse values for pure magnesium, several magnesium—octene-1 slurries, and octene-1 are presented in figure 1(b). Higher air specific-impulse values can be achieved as the percent magnesium in the slurry is increased.



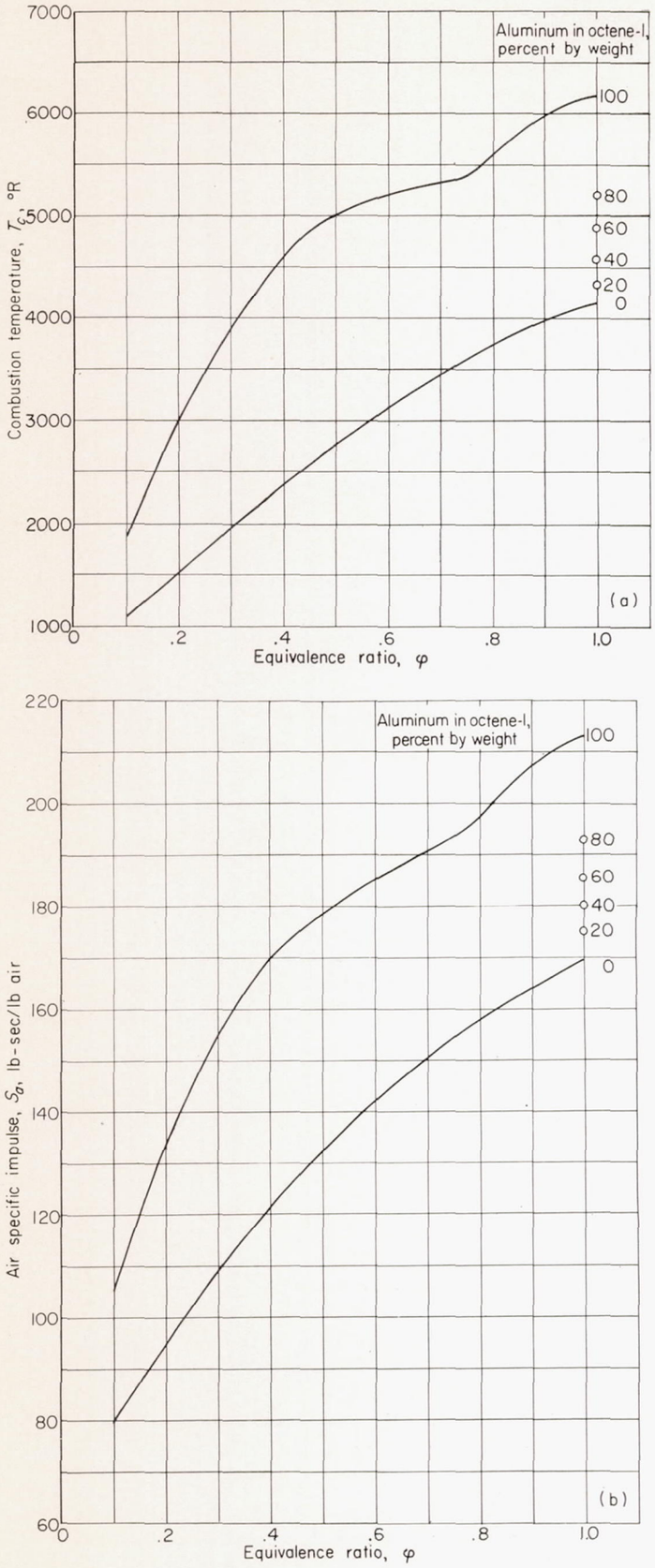
(a) Variation of combustion temperature with equivalence ratio.

FIGURE 1.—Theoretical combustion performance for magnesium, magnesium—octene-1 slurries, and octene-1. Combustor-inlet air temperature, 560° R; inlet air pressure, 2 atmospheres.



(b) Variation of air specific impulse with equivalence ratio.

FIGURE 1.—Concluded.



(a) Variation of combustion temperature with equivalence ratio.

(b) Variation of air specific impulse with equivalence ratio.

FIGURE 2.—Theoretical combustion performance for aluminum, aluminum—octene-1 slurries, and octene-1. Combustor-inlet air temperature, 560° R; inlet air pressure, 2 atmospheres.

ALUMINUM AND ALUMINUM—OCTENE-1 SLURRIES

The combustion temperatures for aluminum, aluminum—octene-1 slurries, and octene-1 are shown in figure 2(a). Included in figure 2(a) are the theoretical combustion temperatures for several concentrations of metal in aluminum—octene-1 slurries at an equivalence ratio of 1.0. The irregular nature of the temperature curve for aluminum is due to a phase transition of aluminum oxide Al_2O_3 from liquid to gas.

The variation of air specific impulse with equivalence ratio for aluminum and octene-1 is presented in figure 2(b). Included in this figure are values of air specific impulse for several aluminum slurries evaluated at an equivalence ratio of 1.0. The air specific impulse increases as the metal concentration in the slurry is increased.

BORON AND BORON—OCTENE-1 SLURRIES

The combustion temperatures for boron and several boron—octene-1 slurries are shown in figure 3(a). The variation of air specific impulse with equivalence ratio for boron, boron—octene-1 slurries, and octene-1 is presented in figure 3(b). Between about 3500° and 4050° R the slope of the combustion temperature curve for boron changes rapidly. At 4050° R there is a discontinuity in the slope of the curve. These effects are caused by the vaporization of boric oxide which absorbs heat. A similar trend is noted in the air specific-impulse curve for boron.

CARBON, HYDROGEN, AND α-METHYLNAPHTHALENE

The combustion temperatures for carbon, hydrogen, α-methylnaphthalene, and octene-1 are shown in figure 4(a). The variation of air specific impulse with equivalence ratio for carbon, hydrogen, α-methylnaphthalene, and octene-1 is presented in figure 4(b). Since the combustion temperatures for carbon, α-methylnaphthalene, and octene-1 are sufficiently close together, a single curve has been drawn for the data.

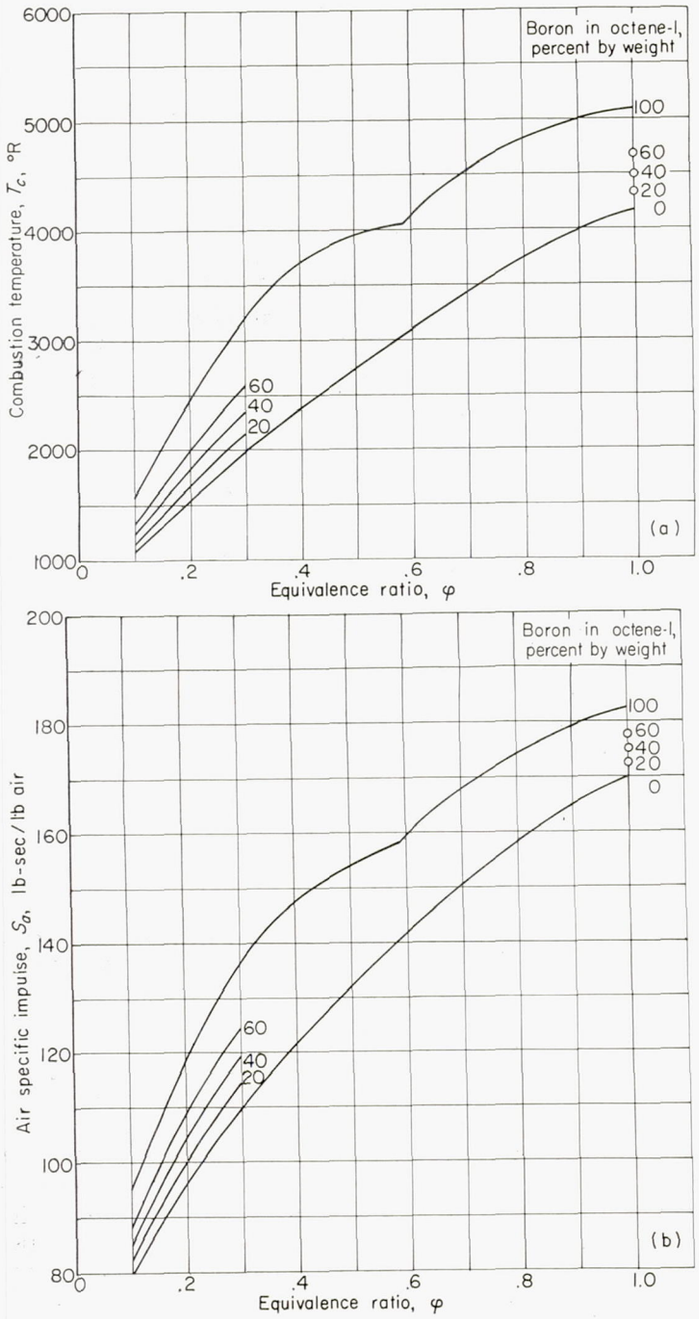
DIBORANE AND PENTABORANE

The combustion temperatures for diborane and pentaborane are compared with those of hydrogen and boron in figure 5(a). The variation of air specific impulse with equivalence ratio for diborane, pentaborane, hydrogen, and boron is presented in figure 5(b). Between about 3500° and 4000° R, the combustion temperature curves for diborane and pentaborane show a trend caused by the vaporization of boric oxide, which is similar to that previously noted for boron. This trend is also present in the curves of air specific impulse for diborane and pentaborane.

Boron, pentaborane, diborane, and hydrogen comprise a sequence in which boron is combined with increasing percentages of hydrogen. In the following table are shown the mole fractions of boron and hydrogen in the fuels and the approximate heat absorbed by vaporizing the boric oxide formed from a pound of each fuel. Also shown is the approximate heat absorbed by vaporizing the boric oxide formed from a pound of stoichiometric fuel-air mixture. These heats of vaporization have been evaluated at a temperature of 3600° R for convenience.

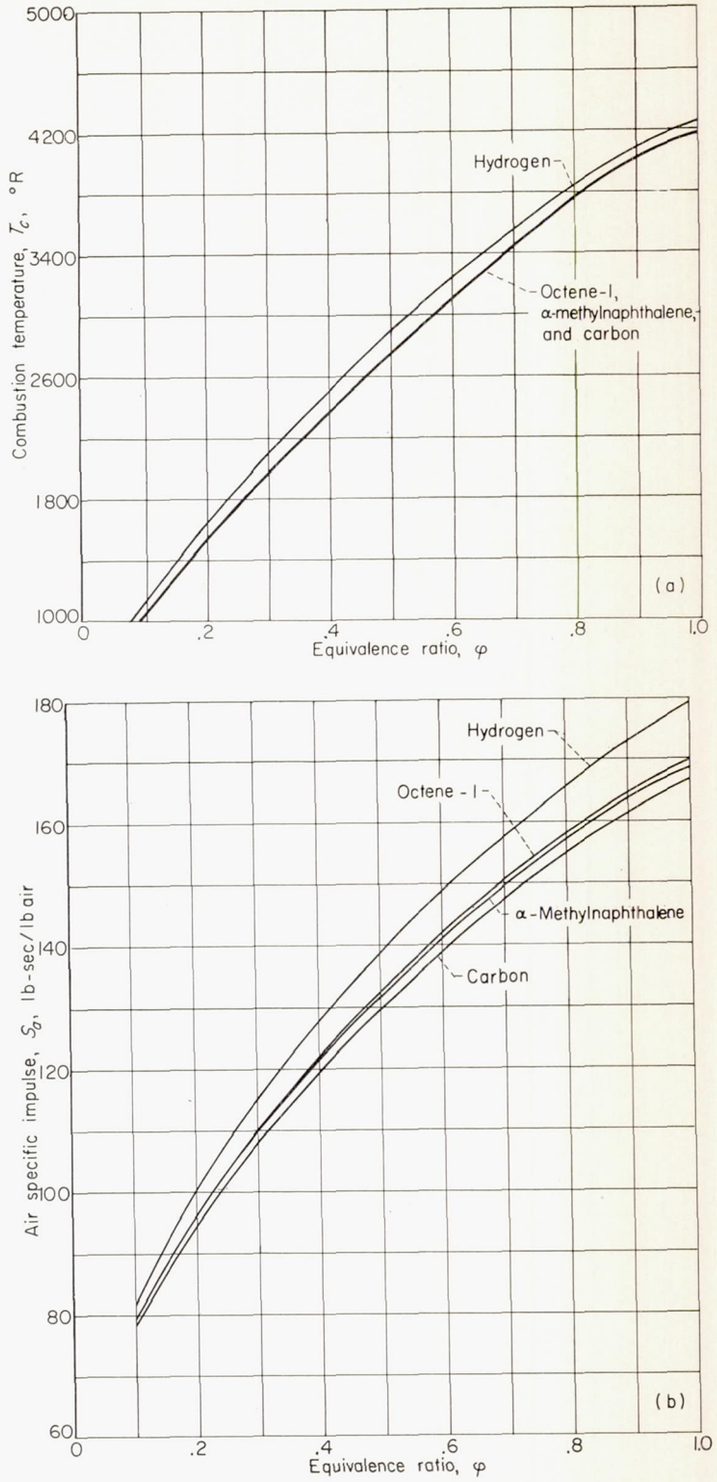
Fuel	Atom fraction of constituents		Heat absorbed by vaporization of boric oxide	
	Boron	Hydrogen	Btu/lb fuel	Btu/lb stoichiometric fuel-air mixture
Boron	1.0	0	6240	591
Pentaborane	.357	.643	5344	379
Diborane	.250	.750	4877	306
Hydrogen	0	1.00	0	0

As suggested by the table, the irregularities in the curves of figure 5 become less severe as the hydrogen content of the fuel is raised because of the decreasing amount of heat absorbed by vaporization of boric oxide.



(a) Variation of combustion temperature with equivalence ratio.
(b) Variation of air specific impulse with equivalence ratio.

FIGURE 3.—Theoretical combustion performance for boron, boron—octene-1 slurries, and octene-1. Combustor-inlet air temperature, 560° R; inlet air pressure, 2 atmospheres.

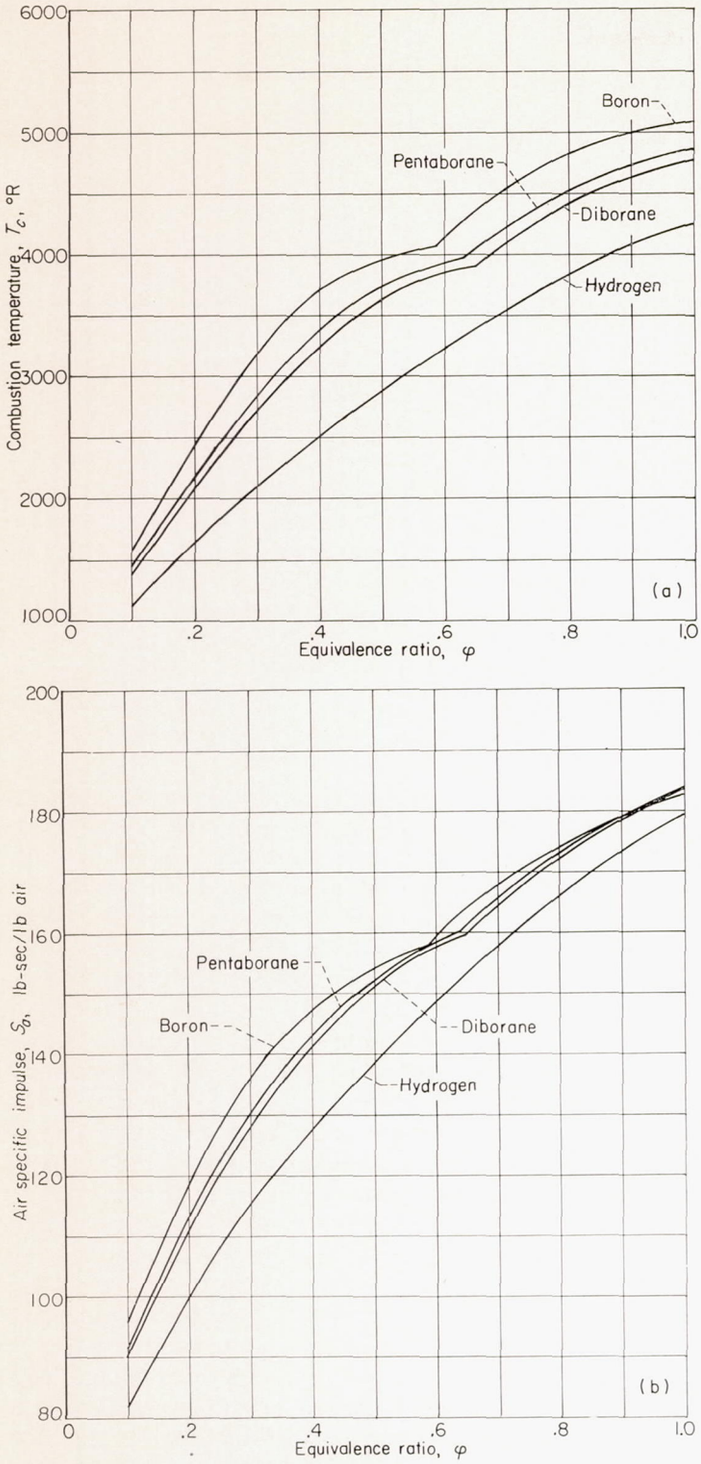


(a) Variation of combustion temperature with equivalence ratio.
(b) Variation of air specific impulse with equivalence ratio.

FIGURE 4.—Theoretical combustion performance for hydrogen, carbon, α-methylnaphthalene, and octene-1. Combustor-inlet air temperature, 560° R; inlet air pressure, 2 atmospheres.

SUMMARY COMPARISONS

The adiabatic constant-pressure combustion temperature and impulse characteristics of magnesium, 50 percent magnesium—octene-1 slurry, aluminum, boron, 50 percent boron—octene-1 slurry, hydrogen, carbon, α-methylnaphtha-



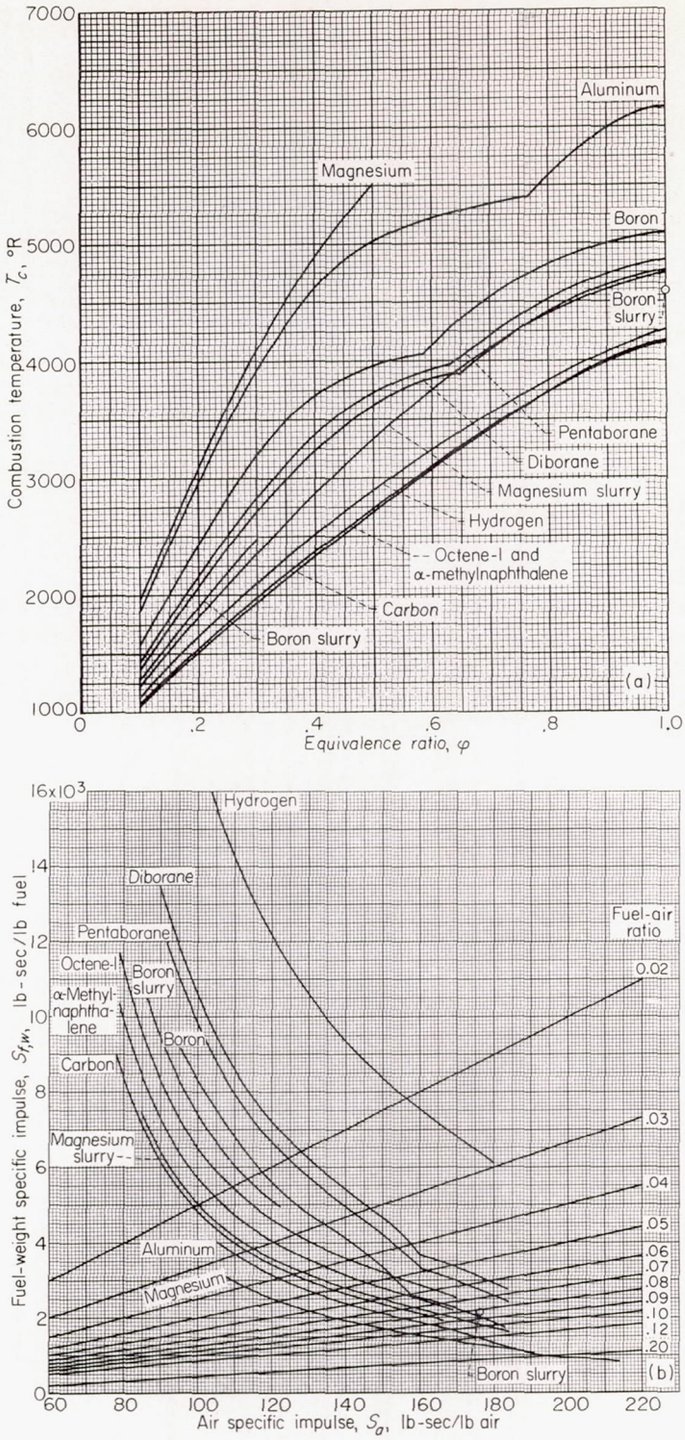
(a) Variation of combustion temperature with equivalence ratio.

(b) Variation of air specific impulse with equivalence ratio.

FIGURE 5.—Theoretical combustion performance for boron, pentaborane, diborane, and hydrogen. Combustor-inlet air temperature, 560° R; inlet air pressure, 2 atmospheres.

lene, diborane, pentaborane, and octene-1 are compared in figure 6. In order to reduce the congestion of the figures, only slurries containing 50 percent metal by weight are included in the summary comparisons.

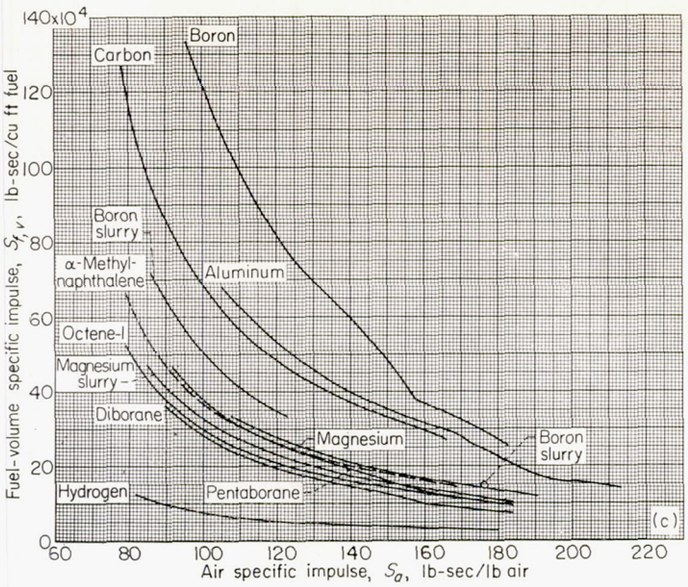
The combustion temperatures for the aforementioned fuels are presented in figure 6(a). The fuels, listed in order of decreasing combustion temperature at equivalence ratios below 0.5, are: magnesium, aluminum, boron, pentaborane, diborane, 50 percent boron—octene-1 slurry, 50 percent magnesium—octene-1 slurry, hydrogen, α-methylnaphthalene, octene-1, and carbon.



(a) Variation of combustion temperature with equivalence ratio.

(b) Variation of fuel-weight specific impulse with air specific impulse.

FIGURE 6.—Summary of combustion performance for representative high-energy fuels. Combustor-inlet air temperature, 560° R; inlet air pressure, 2 atmospheres. (Slurry fuels, 50 percent metal by weight in octene-1.)



(c) Variation of fuel-volume specific impulse with air specific impulse.

FIGURE 6.—Concluded.

These fuels are compared on the basis of fuel-weight specific impulse, an index of fuel economy, and air specific impulse, an index of thrust in figure 6(b). The data in figure 6(b) are presented because comparison of fuel economy for various fuels should be made at the same level of air specific impulse. Also, the relative air specific impulse of several fuels at a fixed value of fuel economy or fuel-weight specific impulse may be of interest. This information and the corresponding fuel-air ratios may be readily obtained from figure 6(b).

The following fuels, evaluated below an air specific-impulse value of 152 seconds, are listed in order of decreasing fuel-weight specific impulse: hydrogen, diborane, pentaborane, boron, 50 percent boron—octene-1 slurry, octene-1, α-methylnaphthalene, 50 percent magnesium—octene-1 slurry, carbon, aluminum, and magnesium. While this order is retained in general above an air specific impulse of 152 seconds, the fuel specific impulse of octene-1 exceeds that of boron above this air specific impulse because of the vaporization of boric oxide B_2O_3.

The maximum obtainable air specific impulse, occurring generally at equivalence ratios exceeding 1.0, was not calculated. However, all fuels except carbon and α-methylnaphthalene appear to have a maximum air specific impulse exceeding that of octene-1, which is 172.8 seconds.

Representative fuels were also evaluated in terms of fuel-volume specific impulse at various air specific-impulse values as shown in figure 6(c). The curves for pure magnesium, aluminum, and boron are based upon the solid densities of the metal. The densities of pentaborane, diborane, and hydrogen were those of the liquids at 536.7°, 325.1°, and 36.6° R, respectively.

The fuels evaluated in order of decreasing fuel-volume specific impulse (increasing volumetric fuel consumption) at an air specific impulse below 152 seconds are as follows: boron, aluminum, carbon, 50 percent boron—octene-1 slurry, magnesium, pentaborane or α-methylnaphthalene, 50 percent magnesium—octene-1 slurry, octene-1, diborane, and hydrogen.

APPLICATIONS OF DATA

The theoretical performance data of figures 1 to 6 can be used for the determination of air specific-impulse efficiency and combustion efficiency. They can also be used in estimating the relative amounts of the various fuels required to maintain a fixed level of thrust in an engine. For these purposes the single combustor-inlet condition of a temperature of 560° R and a pressure of 2 atmospheres will often be too limited. Some of the fuels such as diborane seemed, on the basis of the theoretical performance shown in figures 1 to 6, to be likely candidates for further theoretical and experimental investigation. Other fuels such as carbon, hydrogen, and boron were of interest because they are the elemental constituents of some of the high-performance fuels.

To facilitate the application of the theoretical performance data to the evaluation of experimental data it seemed desirable to extend the range of inlet conditions of these fuels: octene-1, slurry of 50 percent magnesium in octene-1, carbon (graphite), boron (crystal), pentaborane (liquid), diborane (liquid), and hydrogen (liquid). Inlet air temperatures from 560° to 1360° R and combustion pressures from 0.2 to 2 atmospheres were considered. The data are presented in figures 7 to 13.

Parts (a) and (b) of figures 7 to 13 present combustion temperature and air specific impulse, respectively, plotted against equivalence ratio for inlet air temperatures of 560°, 960°, and 1360° R at a combustion pressure of 2 atmospheres. Examination of parts (a) and (b) reveals that a given increase in inlet air temperature results in a diminishing gain in combustion temperature and air specific impulse as equivalence ratio is raised. The higher combustion temperatures associated with increasing equivalence ratio result in increased specific heat and more dissociation of the combustion products. Much of the heat made available by an increase in inlet air temperature is absorbed without a corresponding gain in combustion temperature or air specific impulse.

Parts (c) and (d) present combustion temperature and air specific impulse, respectively, plotted against combustion pressure for an inlet air temperature of 560° R and equivalence ratios from 0.7 to 1.0. At the lower equivalence ratios (below 0.7) the effect of pressure is usually negligible. An exception to this arises with materials containing boron, where the vaporization of boric oxide in the vicinity of an equivalence ratio of 0.4 is pressure dependent. A direct computation is then necessary.

Although the data of parts (c) and (d) of figures 7 to 13 were computed at pressures of only 0.2 and 2 atmospheres, a straight line of combustion temperature or air specific impulse plotted against the logarithm of combustion pressure has been drawn between these pressures for each equivalence ratio. This convenient procedure has been verified for several cases. For instance, combustion temperature and air specific impulse at an equivalence ratio of 1.0 were computed for octene-1 at two additional combustion pressures of 0.6 and 10 atmospheres. These data are represented in figures 7(c) and (d) by the circled points.

This semilogarithmic relation between combustion temperature or air specific impulse and combustion pressure is expected to be valid for all eight fuels reported herein at equivalence ratios from 0.7 to 1.0. Extrapolation of the lines from combustion pressures of 2 to 10 atmospheres is less satisfactory than interpolation between 0.2 and 2 atmospheres. All lines have therefore been dashed above 2 atmospheres. Extrapolation below 0.2 atmosphere may also be less satisfactory.

In parts (c) and (d) the combustion temperature and air specific impulse at a combustion pressure of 0.2 atmosphere are less than those at a combustion pressure of 2 atmospheres within the range of equivalence ratios shown. Moreover, the loss in combustion temperature and air specific impulse with this decrease in combustion pressure is greatest at the richer equivalence ratios. These effects result from the increasing dissociation caused by an increase in temperature or a decrease in pressure.

DETERMINATION OF COMBUSTION TEMPERATURE AND AIR SPECIFIC IMPULSE AT COMBUSTOR-INLET CONDITIONS OTHER THAN THOSE REPORTED

In many instances it is desired to know the combustion temperature and air specific impulse at inlet conditions other than those for which the data of figures 1 to 13 were computed. When the effects of inlet air temperature and combustion pressure are known for a fuel over a range of inlet conditions as in figures 7 to 13, approximate values of air specific impulse at other inlet conditions may be determined as follows.

At equivalence ratios below 0.7 these data can be read directly from the curves of part (a) or (b) without consideration of pressure, with the exception of boron-containing fuels. At equivalence ratios exceeding 0.7 the effect of combustion pressure on combustion temperature and air specific impulse becomes important for all fuels. The effect of combustion pressure on combustion temperature or air specific impulse in this region can be determined in the following manner: The combustion pressure or air specific impulse at the desired inlet air temperature, determined from part (a) or (b) of figures 7 to 13, is entered in part (c) or (d) at a pressure of 2 atmospheres. The combustion temperature or air specific impulse is then corrected to the desired pressure along a line of constant equivalence ratio. For example, the air specific impulse of boron at an equivalence ratio of 0.8, an inlet air temperature of 1260° R, and a combustion pressure of 0.3 atmosphere can be found as follows: From figure 10(b) the air specific impulse is determined as 178.8 seconds for the conditions stated, but at a combustion pressure of 2 atmospheres. The value obtained is entered in figure 10(d) at this pressure and air specific impulse (point A), and a line of constant equivalence ratio is followed to a pressure of 0.3 atmosphere. The desired air specific impulse is found to be 174.9 seconds. This is very close to the value of 175.2 seconds determined by direct computation for a pressure of 0.3 atmosphere.

In making a pressure correction, it may be necessary occasionally to enter data in a figure such as figure 10(d) at an air specific impulse or combustion temperature exceeding the highest line of air specific impulse or combustion temperature plotted against combustion pressure. For example, figure 10(b) indicates an air specific impulse of 186.6 seconds for an equivalence ratio of 1.0, an inlet air temperature of 1360° R, and a combustion pressure of 2 atmospheres. Point C is thus located on figure 10(d) which is above the highest line already present. A correction to a combustion pressure of 0.2 atmosphere, made along a dashed line converging toward existing lines at the same rate at which they converge toward each other, locates an air specific impulse of 181.2 seconds at point D. By direct computation, the value sought is 180.9 seconds.

DETERMINATION OF AIR SPECIFIC-IMPULSE EFFICIENCY AND COMBUSTION EFFICIENCY

Both air specific-impulse efficiency and combustion efficiency may be found for experimental data by the use of the curves presented herein. Air specific-impulse efficiency is defined as the ratio of the experimental air specific impulse to the theoretical air specific impulse at the same equivalence ratio:

$$\eta_{S_a}=\left(\frac{S_{a,exp}}{S_{a,t}}\right)_{\varphi} (\varphi=\text{const.}) \tag{9}$$

The experimental air specific impulse must be computed from experimental measurements as discussed in the appendix; the theoretical air specific impulse is read from the curves of air specific impulse plotted against equivalence ratio for a pressure of 2 atmospheres at the combustor-inlet temperature and equivalence ratio applying to the experimental data. This value may then be corrected to the combustion pressure used in the actual engine by the method described previously.

A combustion efficiency which is often useful can be defined as the ratio of the theoretical equivalence ratio to the experimental equivalence ratio required to produce a given air specific impulse or combustion temperature:

$$\eta_c=\left(\frac{\varphi_t}{\varphi_{exp}}\right)_{T_c} (T_c=\text{const.}) \tag{10}$$

and

$$\eta_c=\left(\frac{\varphi_t}{\varphi_{exp}}\right)_{S_a} (S_a=\text{const.}) \tag{11}$$

Fuel-air ratios may replace equivalence ratios. These definitions are valid only for equivalence ratios of 1.0 or less. When the experimental data are obtained at pressures other than 2 atmospheres, a pressure correction may be applied conveniently to the theoretical equivalence ratio as follows: The experimental combustion temperature or air specific impulse, together with the combustion pressure, is entered on the semilogarithmic graph of theoretical combustion temperature or air specific impulse plotted against combustion pressure (part (c) or (d) of figs. 7 to 13), and a line of constant composition is followed to a combustion pressure of 2 atmospheres. The combustion temperature or air specific impulse, adjusted to the 2-atmosphere standard, and the experimental inlet air temperature are then used on the plots of combustion temperature or air specific impulse plotted against inlet air temperature and equivalence ratio to find the theoretical equivalence ratio. For example,

suppose that boron burned at an inlet air temperature of 960° R, a combustion pressure of 0.2 atmosphere, and an equivalence ratio of 1.0 produces an experimental air specific impulse of 176 seconds, which locates point E on figure 10(d). Following the dashed line of constant composition to point F determines a pressure-adjusted air specific impulse of 180.9 seconds. Locating a point in figure 10(b) at 180.9 seconds and at an inlet air temperature of 960° R determines a theoretical equivalence ratio of 0.89. A combustion efficiency of 0.89 is then found by means of equation (11).

In equations (9) and (11), experimental air specific-impulse data are compared with theoretical data in which expansion at fixed composition is assumed. If the recombination rates are such that some adjustment of composition is obtained in the nozzle, efficiencies computed from these equations will tend to be high when the data of figures 7 to 13 are used since these data are for expansion at fixed composition.

DETERMINATION OF RELATIVE FUEL-FLOW REQUIREMENTS FOR GIVEN ENGINE

In instances where several fuels are being considered for an engine, it may be desired to know the relative amounts of each fuel required to obtain a fixed thrust level. The curves of air specific impulse plotted against equivalence ratio may conveniently be used for determining the amounts of fuel if advantage is taken of the following assumptions: The combustion efficiency is the same for each fuel, and momentum and other internal pressure losses are nearly the same for each fuel at a given thrust level.

For example, a ramjet engine is operated with octene-1 or any other reasonably similar hydrocarbon at an equivalence ratio of 0.737, an inlet air temperature of 560° R, and a combustion pressure of 2 atmospheres. From figure 7(b), the air specific impulse for octene-1 at this equivalence ratio and inlet air temperature is 153.4 seconds. By the use of figures 8(b), 10(b), 11(b), and (12b) for 50 percent magnesium slurry, boron, pentaborane, and diborane, the equivalence ratios required to produce an air specific impulse of 153.4 seconds are determined. These are converted to fuel-air ratios by the formula

$$\frac{w_f}{w_a}=\varphi\left(\frac{w_f}{w_a}\right)_{st} \tag{12}$$

The required equivalence ratios and fuel-air ratios are presented in the following table:

Fuel	Equivalence ratio	Fuel-air ratio	Relative fuel flow
Octene-1	0.737	0.0500	1.00
50 Percent magnesium slurry	.57	.0648	1.30
Boron	.49	.0513	1.03
Pentaborane	.515	.0393	.79
Diborane	.525	.0351	.70

The relative fuel flow is defined in this case as the ratio of the fuel-air ratio of the substitute fuel to that of octene-1.

The stoichiometric fuel-air ratio of slurry is calculated from the expression

$$\left(\frac{w_f}{w_a}\right)_{st}=\frac{0.06781}{1-Cr} \tag{13}$$

where C is 0.8078 for magnesium slurry. The value of C is 0.3519 for boron slurry, 0.7401 for aluminum slurry, and 0.11189 for pentaborane blends.

A correction of fuel-air ratios for combustion pressures other than 2 atmospheres can be made in the manner previously described for equivalence ratios used to determine combustion efficiency.

CONCLUDING REMARKS

An analytical evaluation of the air and fuel specific-impulse characteristics of magnesium, magnesium—octene-1 slurries, aluminum, aluminum—octene-1 slurries, boron, boron—octene-1 slurries, carbon, hydrogen, α-methylnaphthalene, diborane, pentaborane, and octene-1 is presented herein. While chemical equilibrium was assumed in the combustion process, the expansion was assumed to occur at fixed composition.

At a fixed air specific impulse below 152 seconds, the fuel weight specific impulses of hydrogen, diborane, pentaborane, boron, and boron—octene-1 slurries were superior to octene-1 for a combustor-inlet air temperature of 560° R and a pressure of 2 atmospheres. At air specific-impulse values of about 152 seconds and higher, the vaporization of boric oxide B_2O_3 for the fuels containing boron reduced the fuel specific impulse relative to octene-1.

The fuel-volume specific impulses of boron, aluminum, carbon, slurries of 50 percent boron and 50 percent octene-1 by weight, magnesium, pentaborane, α-methylnaphthalene, and slurries of 50 percent magnesium and 50 percent octene-1 by weight were superior to octene-1 for an inlet air temperature of 560° R and a combustion pressure of 2 atmospheres.

The effects of inlet air temperature and combustion pressure were investigated for the following fuels: octene-1, 50 percent magnesium slurry, boron, pentaborane, diborane, hydrogen, and carbon. Because a limited range of inlet air temperatures and combustion pressures was considered, methods of extending the data to other inlet conditions were presented.

Determination of air specific-impulse efficiency and combustion efficiency for experimental combustion by means of the theoretical data herein was considered. The use of the theoretical performance data in determining the relative flows of the various fuels to an engine operating at a fixed thrust level was discussed.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, *September 14, 1953*

APPENDIX—COMPUTATION OF AIR SPECIFIC IMPULSE FROM EXPERIMENTAL DATA

The determination of air specific-impulse efficiency requires that the experimental air specific impulse be computable. Suitable measurements of pressure, drag, and thrust must be made on the experimental engine or combustor to permit computation of the stream thrust at the end of the exhaust nozzle:

$$F_e=\left(pA+\frac{wV}{g}\right)_e \tag{A1}$$

This equation is then reduced to the stream thrust function at a condition of sonic flow:

$$F_e^*=\frac{\left(pA+\frac{wV}{g}\right)_e}{\Phi(M_e)} \tag{A2}$$

where

$$\Phi(M_e)=\frac{1+\gamma_e M_e^2}{M_e\sqrt{2(\gamma_e+1)\left(1+\frac{\gamma_e-1}{2}M_e^2\right)}} \tag{A3}$$

The experimental air specific impulse is then

$$S_a=\frac{F_e^*}{w_a} \tag{A4}$$

The Mach number at the exhaust-nozzle outlet can be estimated from the equation

$$M_e=\sqrt{\frac{w_{g,e}V_e}{\gamma_e g p_e A_e}} \tag{A5}$$

For convenience, $\Phi(M_e)$ may be found from tables 30 to 35 of reference 14 as the term F/F^*. The expression $\Phi(M)$ is relatively insensitive to γ, in the neighborhood of M equal to 1.0, as shown in the following table:

M	$F/F^*=\Phi(M)$	
	$\gamma_e=$ 1.1	$\gamma_e=$ 1.4
0.7	1.0599	1.0451
.8	1.0231	1.0185
.9	1.0051	1.0034
1.0	1.0000	1.0000
1.1	1.0041	1.0030
1.2	1.0148	1.0108
1.3	1.0305	1.0217

It must be observed that, if M_e is determined by equation (A5), the error in $\Phi(M_e)$, which results from an incorrect choice of γ_e, will exceed that shown in the preceding table. Data in reference 5 show that a satisfactory value of γ_e at high combustion temperatures (or high air specific impulse) would be 1.2 to 1.3; at low air specific impulse or combustion temperature, values of 1.3 to 1.4 can be employed.

Because equation (A3) is based on the assumption of expansion at fixed composition, it cannot be used to correct experimental data to sonic conditions when there is reason to believe that appreciable recombination has occurred.

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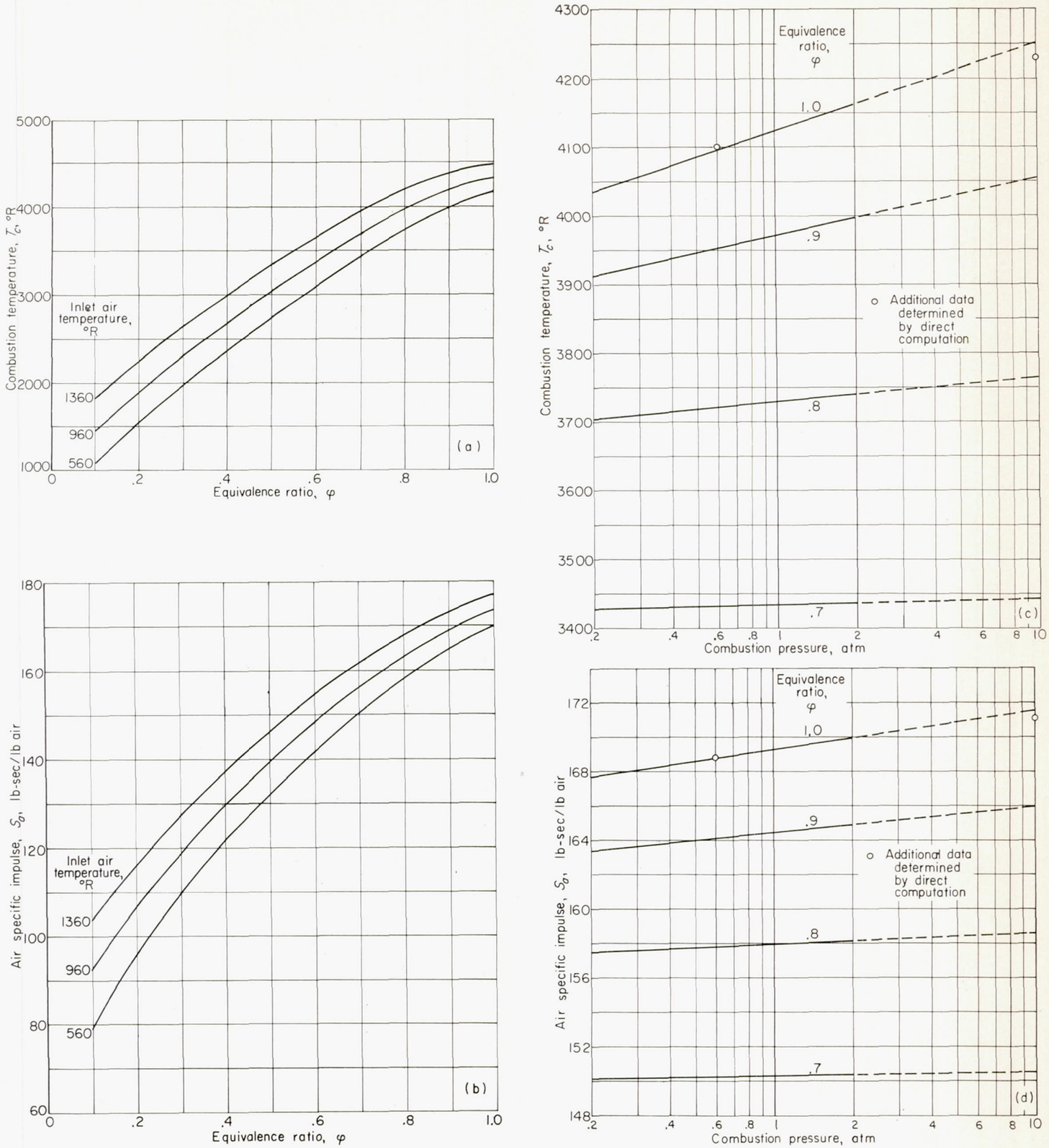


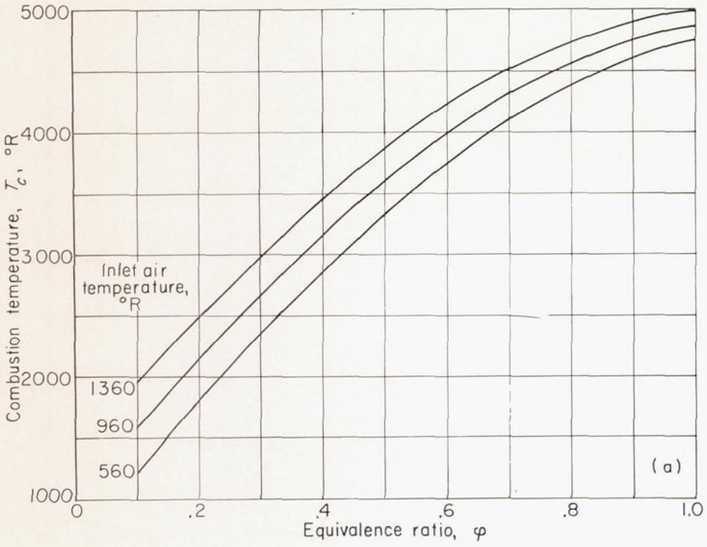
(a) Variation of combustion temperature with equivalence ratio and inlet air temperature. Combustion pressure, 2 atmospheres.

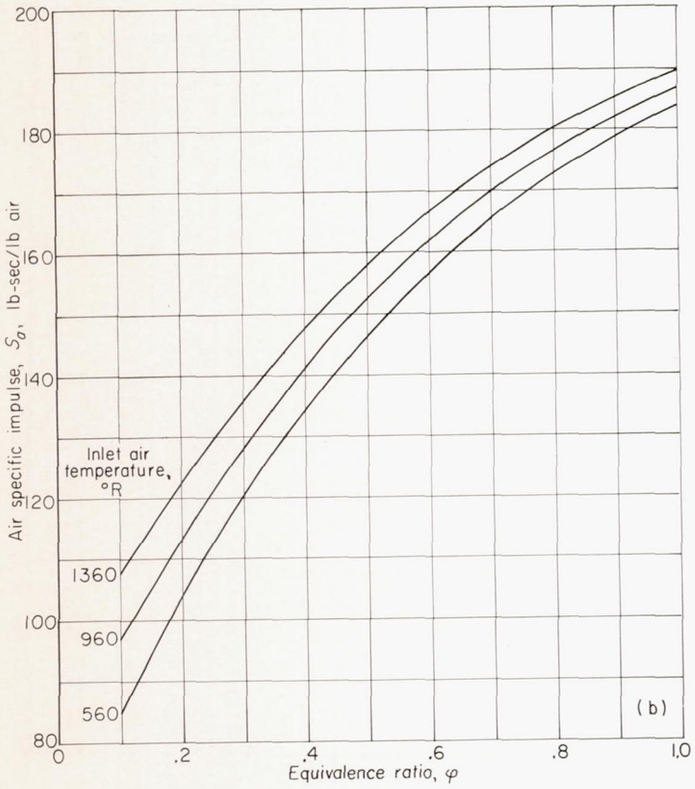
(b) Variation of air specific impulse with inlet air temperature and equivalence ratio. Combustion pressure, 2 atmospheres.

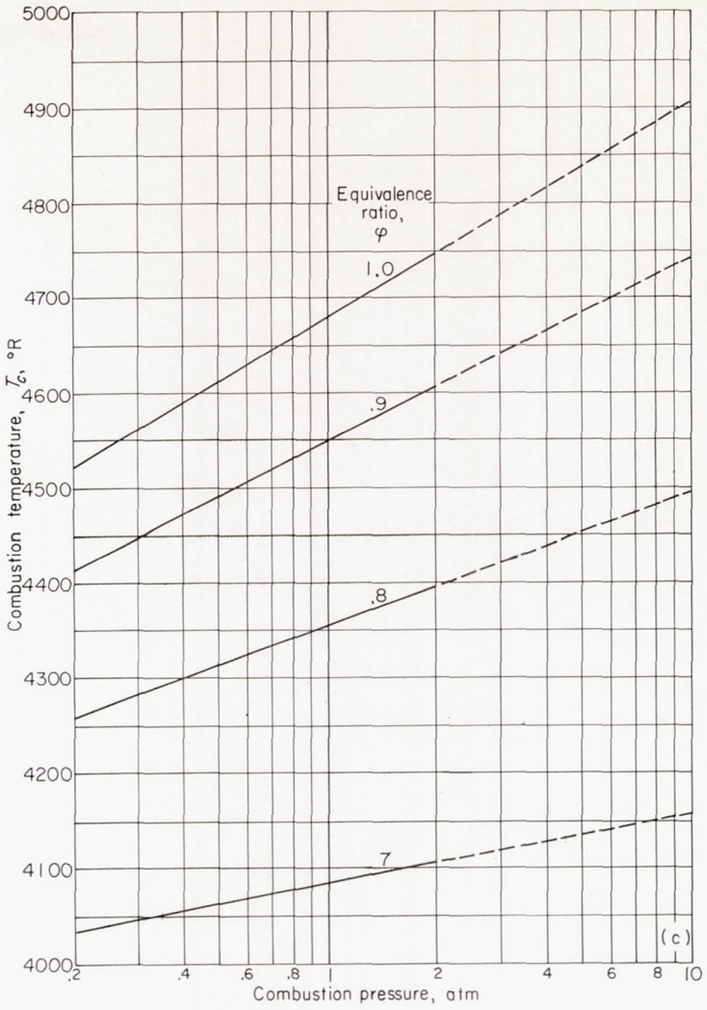
(c) Variation of combustion temperature with combustion pressure at selected equivalence ratios. Inlet air temperature, 560° R.

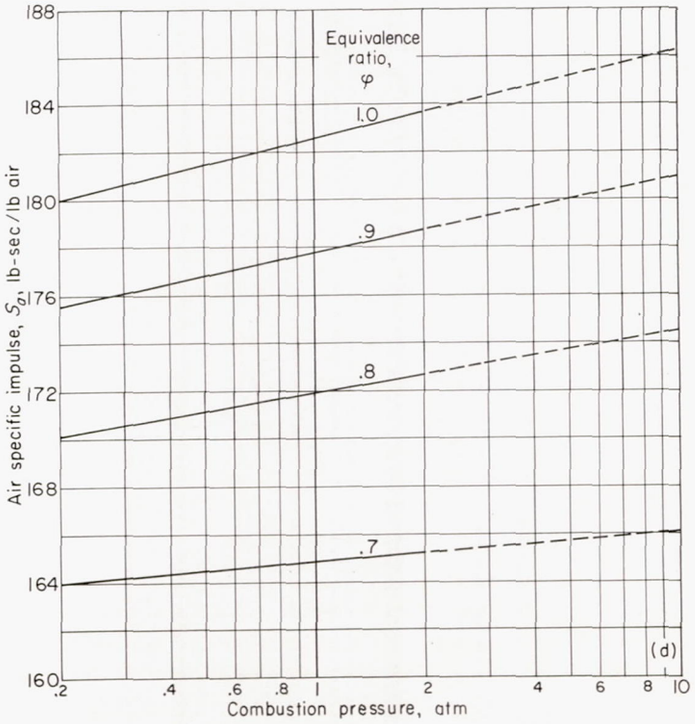
(d) Variation of air specific impulse with combustion pressure at selected equivalence ratios. Inlet air temperature, 560° R.

FIGURE 7.—Effect of ramjet combustor-inlet conditions on theoretical combustion performance of liquid octene-1.









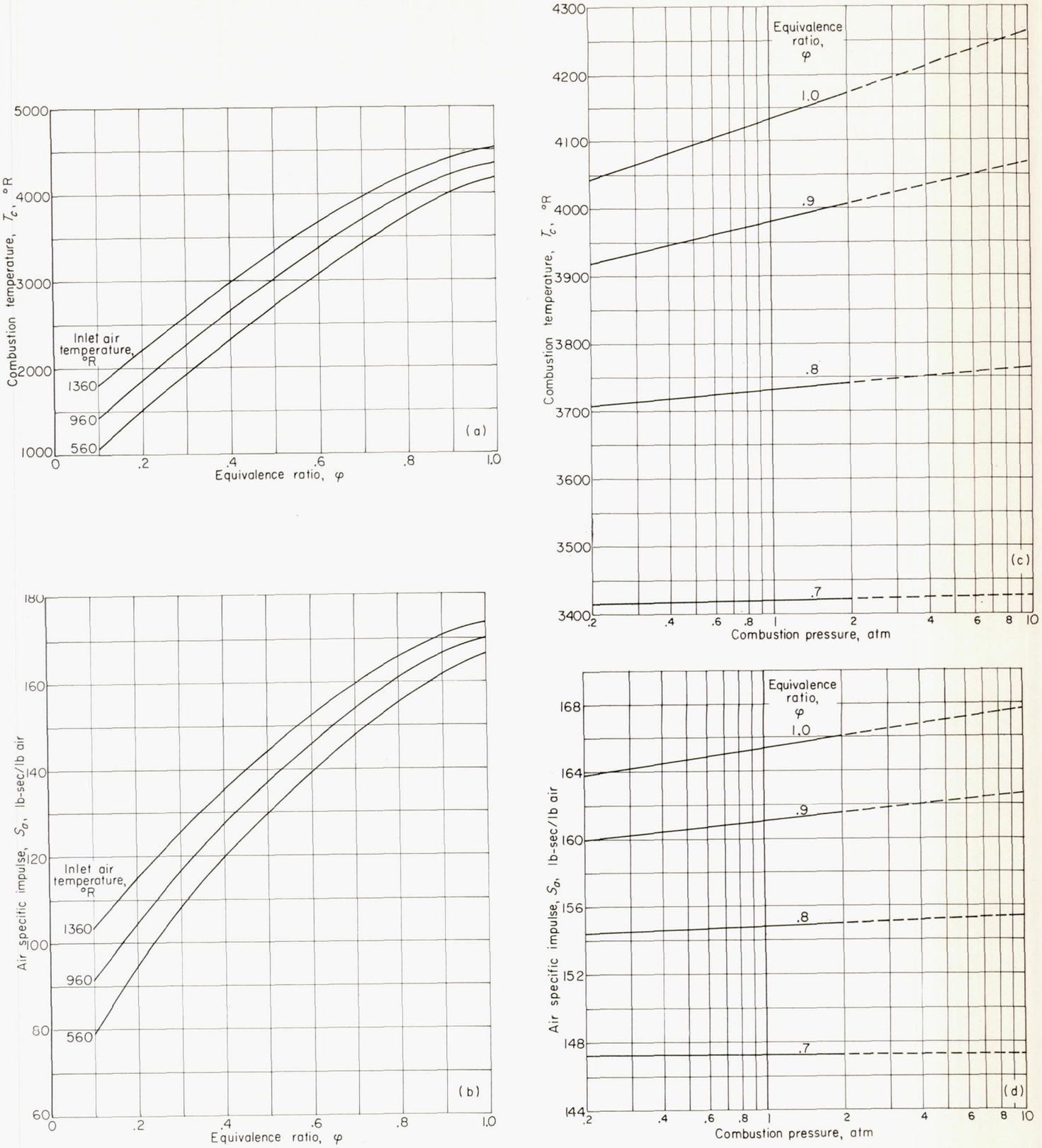
(a) Variation of combustion temperature with equivalence ratio and inlet air temperature. Combustion pressure, 2 atmospheres.

(b) Variation of air specific impulse with inlet air temperature and equivalence ratio. Combustion pressure, 2 atmospheres.

(c) Variation of combustion temperature with combustion pressure at selected equivalence ratios. Inlet air temperature, 560° R.

(d) Variation of air specific impulse with combustion pressure at selected equivalence ratios. Inlet air temperature, 560° R.

FIGURE 8.—Effect of ramjet combustor-inlet conditions on theoretical combustion performance of 50 percent magnesium slurry.



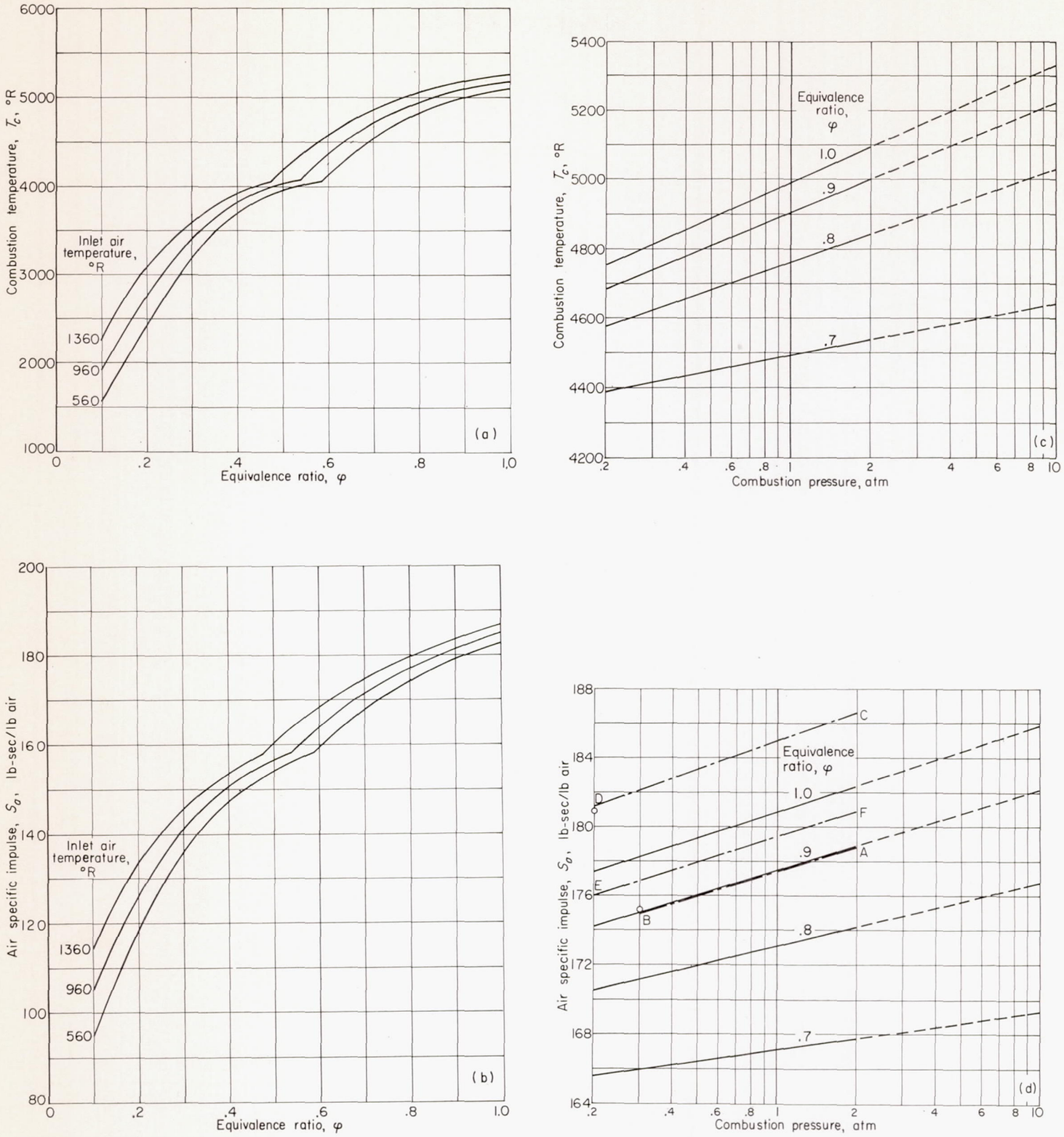
(a) Variation of combustion temperature with equivalence ratio and inlet air temperature. Combustion pressure, 2 atmospheres.

(b) Variation of air specific impulse with equivalence ratio and inlet air temperature. Combustion pressure, 2 atmospheres.

(c) Variation of combustion temperature with combustion pressure at selected equivalence ratios. Inlet air temperature, 560° R.

(d) Variation of air specific impulse with combustion pressure at selected equivalence ratios. Inlet air temperature, 560° R.

FIGURE 9.—Effect of ramjet combustor-inlet conditions on theoretical combustion performance of carbon (graphite).



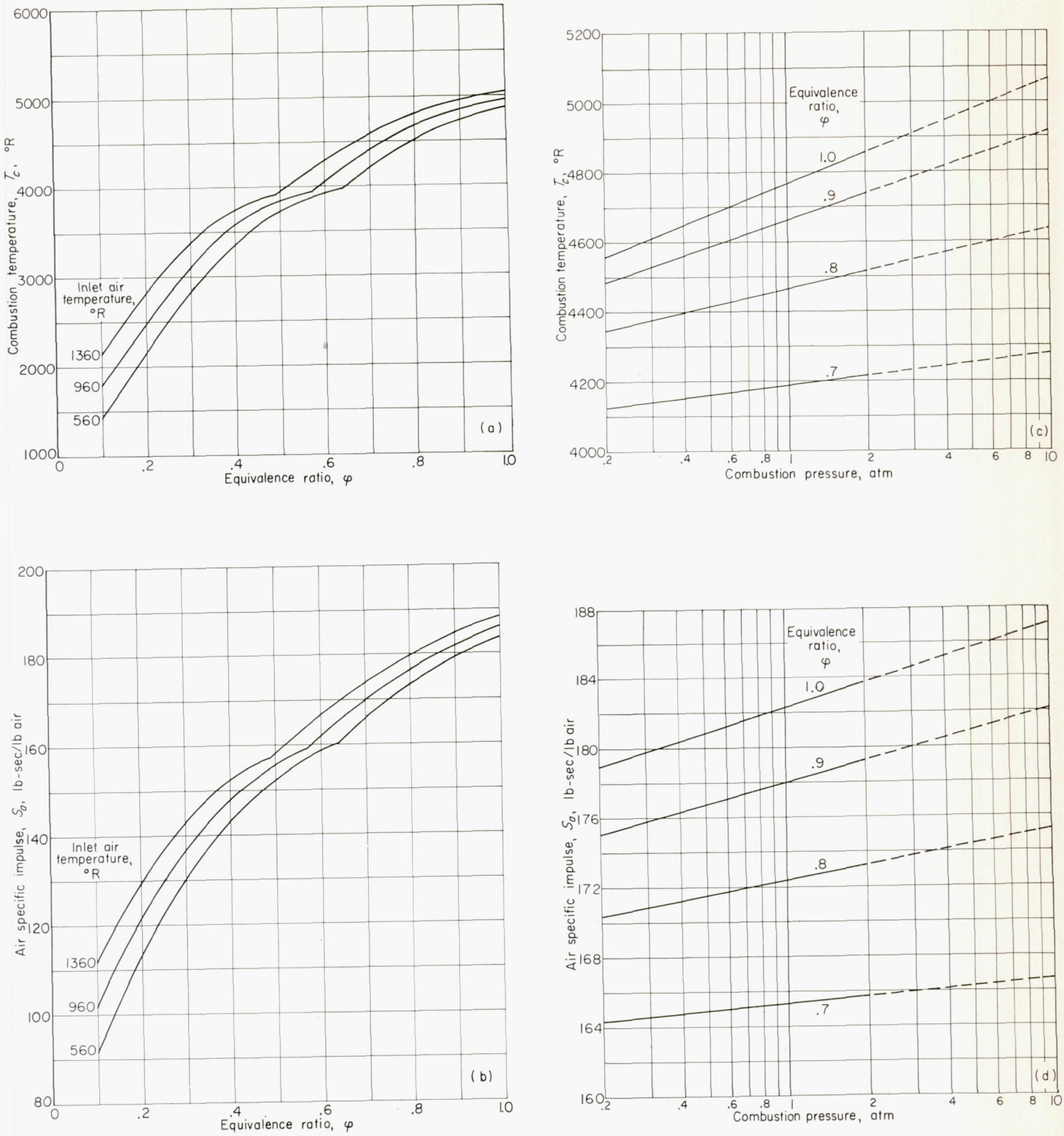
(a) Variation of combustion temperature with inlet air temperature and equivalence ratio. Combustion pressure, 2 atmospheres.

(b) Variation of air specific impulse with inlet air temperature and equivalence ratio. Combustion pressure, 2 atmospheres.

(c) Variation of combustion temperature with combustion pressure at selected equivalence ratios. Inlet air temperature, 560° R.

(d) Variation of air specific impulse with combustion pressure at selected equivalence ratios. Inlet air temperature, 560° R.

FIGURE 10.—Effect of ramjet combustor-inlet conditions on theoretical combustion performance of crystalline boron.



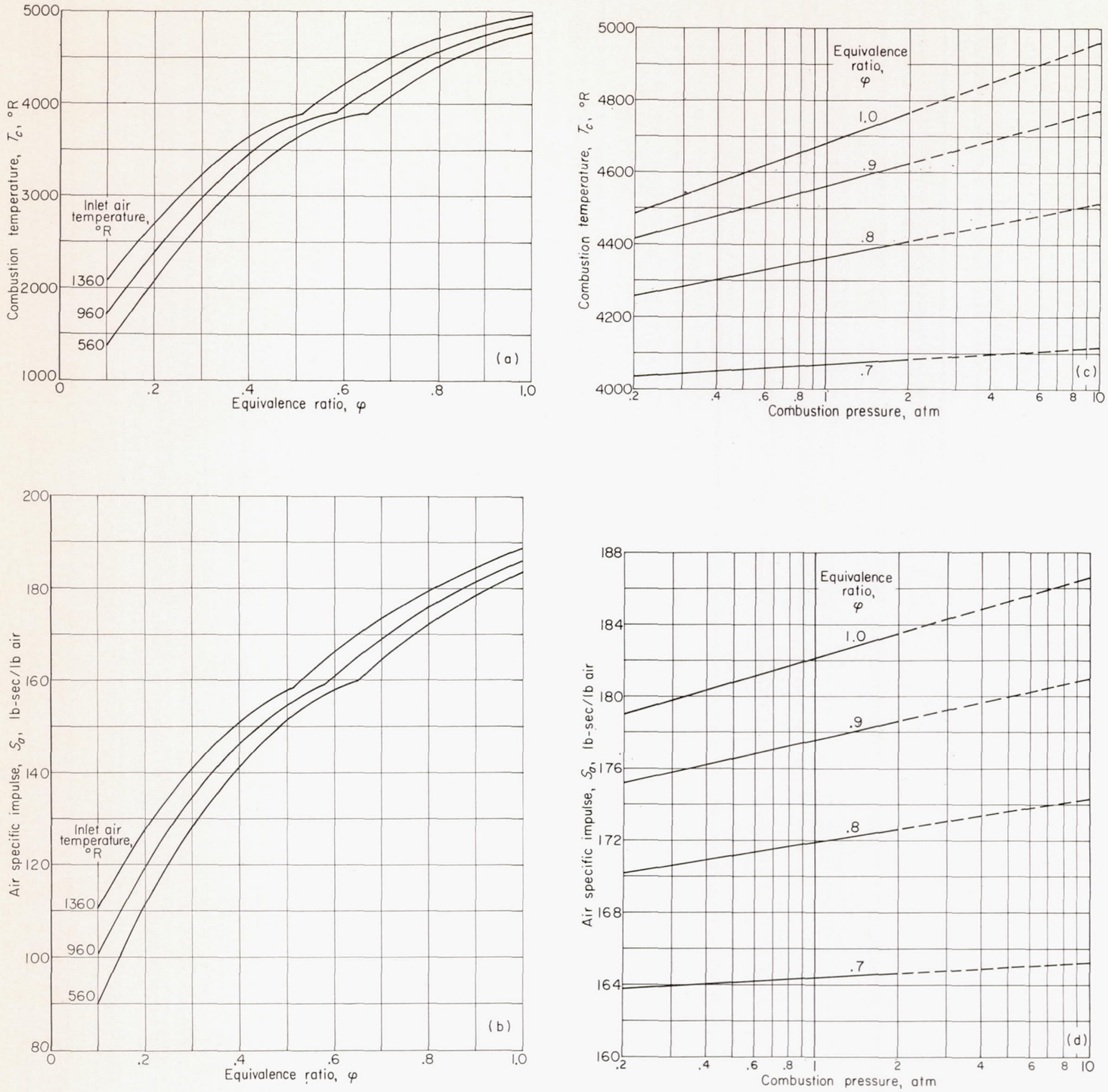
(a) Variation of combustion temperature with equivalence ratio and inlet air temperature. Combustion pressure, 2 atmospheres.

(b) Variation of air specific impulse with inlet air temperature and equivalence ratio. Combustion pressure, 2 atmospheres.

(c) Variation of combustion temperature with combustion pressure at selected equivalence ratios. Inlet air temperature, 560° R.

(d) Variation of air specific impulse with combustion pressure at selected equivalence ratios. Inlet air temperature, 560° R.

FIGURE 11.—Effect of ramjet combustor-inlet conditions on theoretical combustion performance of liquid pentaborane.



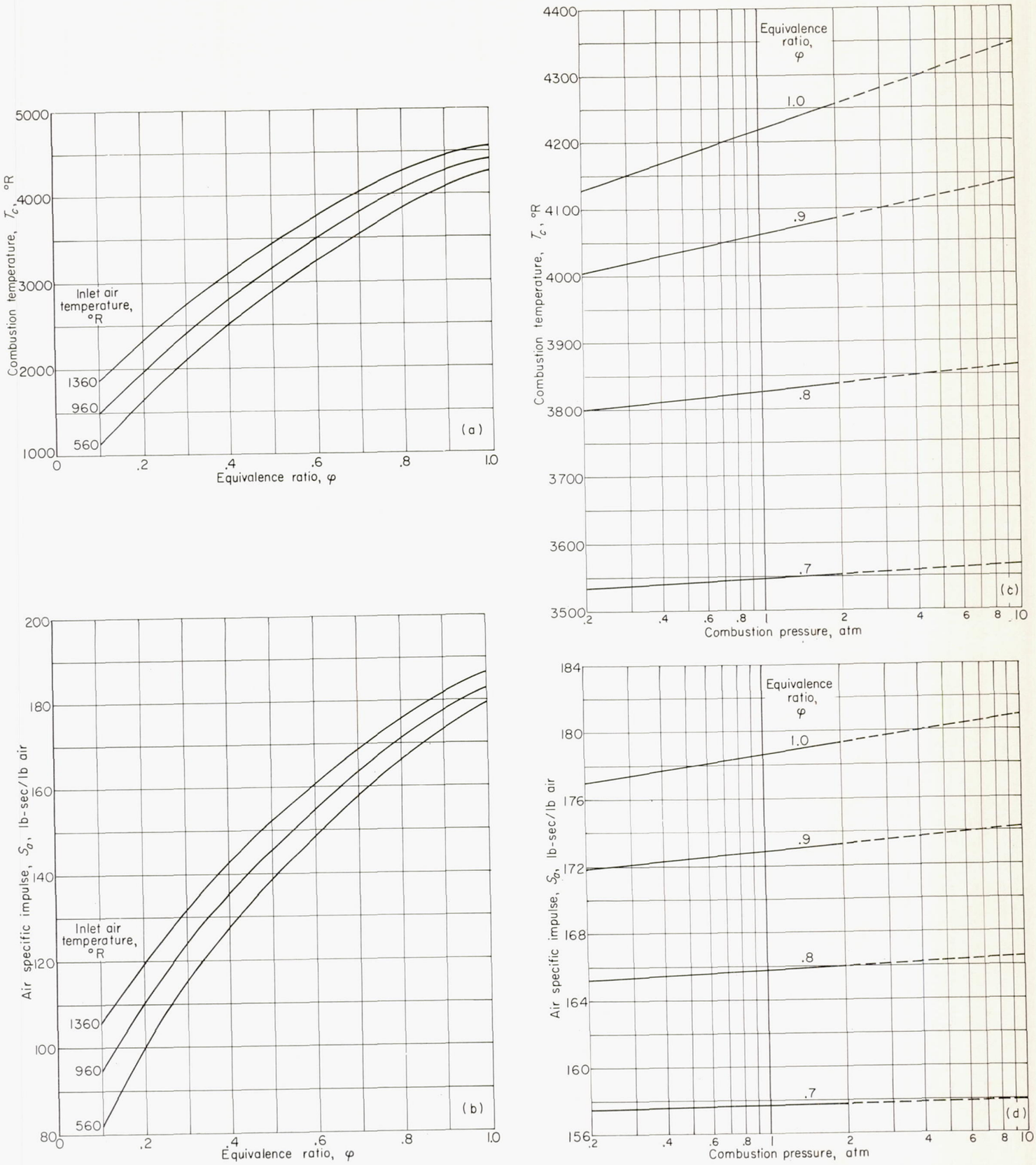
(a) Variation of combustion temperature with equivalence ratio and inlet air temperature. Combustion pressure, 2 atmospheres.

(b) Variation of air specific impulse with inlet air temperature and equivalence ratio. Combustion pressure, 2 atmospheres.

(c) Variation of combustion temperature with combustion pressure at selected equivalence ratios. Inlet air temperature, 560° R.

(d) Variation of air specific impulse with combustion pressure at selected equivalence ratios. Inlet air temperature, 560° R.

FIGURE 12.—Effect of ramjet combustor-inlet conditions on theoretical combustion performance of liquid diborane.



(a) Variation of combustion temperature with equivalence ratio and inlet air temperature. Combustion pressure, 2 atmospheres.

(b) Variation of air specific impulse with inlet air temperature and equivalence ratio. Combustion pressure, 2 atmospheres.

(c) Variation of combustion temperature with combustion pressure at selected equivalence ratios. Inlet air temperature, 560° R.

(d) Variation of air specific impulse with combustion pressure at selected equivalence ratios. Inlet air temperature, 560° R.

FIGURE 13.—Effect of ramjet combustor-inlet conditions on theoretical combustion performance of liquid hydrogen.

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